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HEAT AND MASS TRANSFER IN THE CONCRETE OF SPECIAL INDUSTRIAL INSTALLATIONS

I.V. Zasedatelev and V.G. Petrov-Denisov

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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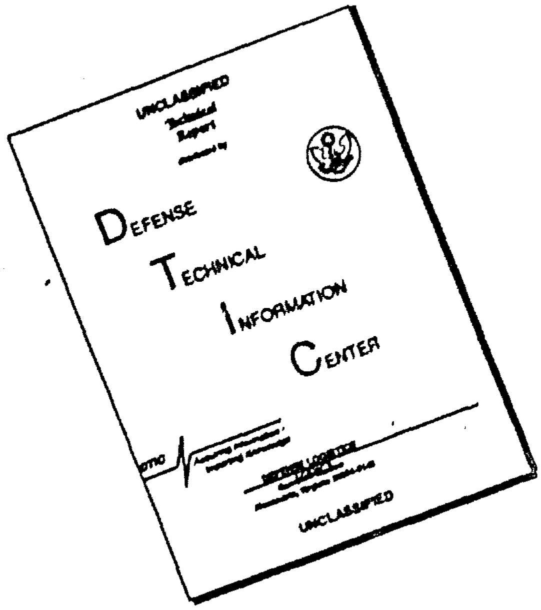

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The basis of this work was results of theoretical and experimental investigations of special features of the heat and mass transfer processes in concrete. Examination and analysis of mathematical models of the processes, experimental determination of their thermal and physical characteristics and the elaboration of effective mathematical means of solving practical problems are included in this report.

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LIST OF BASIC SYMBOLS

t	- temperature, degrees;
[illegible]	- mass transfer potential, mass exchange, degrees;
R	- characteristic size of body, meters;
P	- pressure, kgs/m^2;
C	- expenditure of cement, kg/m^2;
[illegible]	- volumetric mass, kg/m^3;
[illegible]	- density, kg/m^3;
[illegible]	- heat transfer coefficient, $kcal/m\cdot hr\cdot {}^\circ C$;
[illegible]$_m$	- mass transfer coefficient, $kg/m\cdot hr\cdot {}^\circ M$;
a	- temperature transfer coefficient, m^2/hr;
a_m	- moisture diffusion coefficient, m^2/hr;
[illegible]	- heat emission coefficient, $kcal/m^2\cdot hr\cdot {}^\circ C$;
[illegible]$_m$	- mass emission coefficient, $kg/m^2\cdot hr\cdot {}^\circ M$;
c	- specific heat capacity, $kcal/kg\cdot {}^\circ C$;
c_m	- specific mass capacity, $kg/kg\cdot M$;
[illegible]	- thermogradient coefficient, $k/^\circ$ or $^\circ M$/degree;
u	- water content, kg/kg;
W	- moisture, %;
r	- heat of phase transition, kcal/kg;
b	- heating speed, $^\circ$/hr;
m	- rate of regular cooling of body, 1/hr;
g	- acceleration of force of gravity, m/hr^2;
[illegible]	- coefficient of kinematic viscosity, m^2/hr;
[illegible]	- coefficient of volumetric expansion, $1/^\circ$;
q	- density of heat flow, $kcal/m^2\cdot hr$;
q_m	- density of mass flow, $kg/m^2\cdot hr$;
$Fo=\frac{a\tau}{R^2}$	- Fourier's criterion, heat exchange;
$Fo_m=\frac{a_m\tau}{R^2}$	- Fourier's criterion, mass exchange;
$Bi=\frac{\alpha R}{\lambda}$	- Biot's criterion, heat exchange;
$Bi_m=\frac{\alpha_m R}{\lambda_m}$	- Biot's criterion, mass exchange;
$Pd=\frac{bR^2}{a[t_c-t(x,0)]}$	- Predvoditelev's criterion;
$Pn=\frac{\delta_m(t_0-t_c)}{\theta_0}$	- Posnov's criterion;

$Nu = \frac{\alpha R}{\lambda}$ - Nussel't's [Translator's Note: as in text] criterion; heat exchange

$Nu_m = \frac{\alpha_m R}{\lambda_m}$ - Nussel't's criterion, mass exchange;

$Pr = \frac{a}{\nu}$ - Prandtl's criterion, heat exchange;

$Pr_m = \frac{a_m}{\nu}$ - Prandtl's criterion, mass exchange;

$Lu = \frac{Fo_m}{Fo} = \frac{a_m}{a}$ - Lykov's criterion;

$Gr = \beta \frac{gR^3}{\nu^2} \Delta t$ - Grasgof's criterion.

Indices

- 0 - initial state;
- d - dry, parameters of environment;
- p - surface parameters;
- c - parameters of body center;
- mo - moist;
- e - equilibrium value;
- m - mass exchange.

Introduction

The development of energy-related and industrial construction is associated with the erection and start-up of the large number of special structures and installations based on cast in-situ concrete and ferro-concrete. In contrast to operating conditions in residential, civil and public buildings, cast in-situ concrete and ferro-concrete in such industrial installations as industrial smokestacks, cooling towers, shafts, industrial furnaces, and tall towers operate under complex temperature and moisture conditions, are exposed to aggressive environmental influences and operate under the action of large static and dynamic loads.

The high requirements levied on special industrial installations can be met only by a combined solution to the problem: designing the installation components with allowance for the actual operating modes, developing concrete mixtures with the necessary properties, using advanced methods of erecting structures and improved concrete seasoning conditions, predicting the reliability and longevity of the concrete's service throughout the range of the installation's operating conditions.

In order to solve these problems, it is primarily necessary to have knowledge of the physical and technical properties of the concrete under conditions where external factors act upon it. In this case it is necessary to classify the concrete's properties as a function of its hardening stages. Despite the fact that concrete, in contrast to the majority of materials, under normal conditions constantly hardens as it ages and the processes of its hardening continue for decades, it is necessary to devote special attention to the initial stage of its hardening: the stage of active structure-formation.

The initial hardening stage determines to a great extent the ultimate technical properties of the concrete, and the use of certain types of mechanical, chemical, moisture and heat action on the hardening system during this period makes it possible to control the structure-formation process to a certain extent. To optimize the interaction modes, in addition to knowing the kinematics of the chemical and physiochemical processes which are fairly well studied, it is necessary to have a clear concept of the physical processes which take place in the concrete during the structure-formation period.

When special cast in-situ installations are being erected, especially great significance is accorded to the action of heat on the hardening concrete, which is an unavoidable phenomenon primarily when building concrete installations under low-temperature conditions (in winter, during contact with frozen rock, in a watery environment). In contrast to foreign practice, all special facilities in our country are constructed all through the year, which is especially important for the wide-open areas of Siberia and the Far North. The theory in practice of winter concreting, which have been most completely developed by Soviet scientists, create the basic prerequisites for properly selecting the methods of maintaining concrete in special installations. However, the methods and conditions under which heat acts on concrete with regard to both technology and energy can be optimized only if there is a significant expansion of our concepts concerning the physical processes which take place in concrete.

The intensive heat and moisture effects of the environment and the instability of the processes of heat and moisture transfer in the concrete structures of the special installations during operation cause considerable heat and moisture currents and at the same time temperature and moisture gradients in the structures. All of this causes structural deformations in the material, as well as a reduction in the strength and service life of the concrete. The phase moisture transitions which accompany the transfer of heat and mass in the structures also tend to intensify the destructive processes in the concrete.

Thus, heat and mass exchange processes play an important, and perhaps even decisive role in the service life of concrete structures. Therefore it is evidently necessary to study the mechanism of the transfer of moisture and humidity in concrete both during the hardening period and during the operational period, to further perfect calculating methods to predict the heat and mass transfer processes and to determine temperature fields.

Revelation of the special features of the heat and mass transfer processes in concrete, an examination and analysis of mathematical models of the processes, experimental determination of their thermal and physical characteristics and the elaboration of effective mathematical means of solving practical problems comprise the set of tasks which the authors have decided to examine in this work.

The basis of this work was results of theoretical and experimental investigations carried out between 1965 and 1970 by the thermal-physical studies laboratory of the All-Union Scientific Research and Design Institute Teploproyekt, as well as data from productivity studies on facilities of the Ministry of Mounted and Special Construction Projects of the USSR.

The authors would like to express gratitude to laboratory researchers L. A. Maslennikov, G. Z. Mishin, A. M. Pichkov, I. V. Dudinkov, A. Ye. Kulago, Ye. I. Bogachev, E. V. Korotkovaya, A. N. Moro, G. S. Dobryanskaya and G. A. Zhil'kov, who, under the direction of the authors, carried out a number of investigations, studies, calculations and productivity tests, the results of which are given in the book.

CHAPTER VI

METHODS AND CONDITIONS OF THE ACTION OF HEAT ON CONCRETE

Winter Concreting of Cast In-Situ Tall Industrial Facilities

The theory of winter concreting created in our country and the great amount of experience acquired in Soviet industrial construction [67, 68, 69] have provided a great deal of aid in solving the problem of developing proper methods and optimum conditions for heat to act on concrete during the winter concreting of special industrial ferro-concrete cast in-situ facilities.

The most complex aspect of selecting the proper methods for heat to act on the concrete of special facilities consists of the fact that the efficiency of the method, from the viewpoint of energy expenditure and convenience of engineer design, does not always coincide with the advisability of using it to guarantee the necessary technical properties of the concrete in the special installation. In addition, structural features of the special facilities practically rule out the possibility of using a number of effective concrete seasoning methods [70, 35, 41-42], which are widely used in the winter concreting of ordinary cast in-situ structures (thermos, anti-frost additives).

As a rule, in the winter concreting of special facilities it is advisable to use seasoning methods which take advantage of the effect of heat on drying concrete. However, the well-known methods of seasoning concrete in cast in-situ installations do not always satisfy the specific requirements levied on the technology of erecting the facilities. This fact makes it possible to place extremely firm limits on the use of methods to thermally affect concrete [39] and at the same time to develop new methods which correspond more completely to the specific features of the structures and technology of erecting special facilities, as well as the requirements levied on the technical properties of the concrete.

The most universal method of accelerating concrete hardening in cast in-situ thin-walled structures is to heat the concrete in a heated mold, which is a metallic mold equipped with thermal inserts with various types of electrical heating elements.

Until recently, the use of electrical heating of concrete in a heating mold was carried out without having been submitted to thermotechnical calculation both of the systems and the conditions of heating, which were selected essentially by the empirical method. There was primarily no careful regulation of the use of unilateral heating. During unilateral heating an unfavorable picture is observed in the formation of a temperature field not only through the thickness of the wall, but also throughout the height of the heated strip (Figure VI.1).

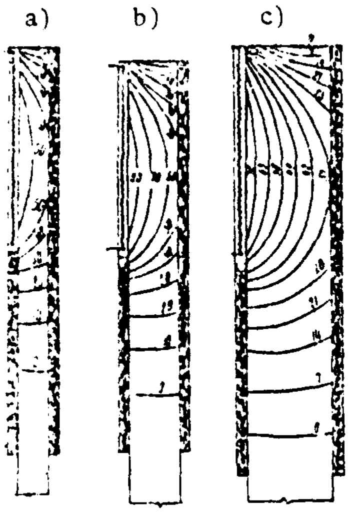

Figure VI.1. Temperature Field When Heating Concrete Unilaterally.

a - Thickness of the Concrete Wall 150 mm; b - same, 250 mm; c - same, 500 mm

The solution to the problems of electrically heating the concrete of special installations (cooling towers, coal bunkers, impact testers), as worked out by the AUSRDI Teploproyekt on analog computers and then tested under bench and industrial conditions, have made it possible to propose new heating insert designs and recommend optimum heat delivery systems and efficient temperature regulation methods [101]. To a considerable extent the new heating insert design compensates for heat losses through the ends of the strip of heated concrete and reduces the temperature gradient throughout the height of the strip to 15-20°C (instead of the 40-50°C, previously observed in the objects).

An analysis of the temperature fields demonstrates the advisability of using unilateral heating for walls no thicker than 0.2 m.

An extremely important factor for ensuring a long service life for the installations is the quality of the concrete in the concreting seams, the zones subject to the least favorable conditions, and the butt sections of the heated strip.

The most effective solution to this problem is to switch to two-stage heating of the concrete with simultaneous shift of the concreting seam 100-150 mm below the edge of the mold. The temperature field in this case may be practically uniform within the limits of the two stages, which considerably improves the concrete hardening conditions in the area of the working concreting seam. This system was first implemented in erecting the Moscow television tower.

The temperature modes for seasoning the concrete in special facilities should reduce destructive processes in the concrete to a minimum. For this purpose a temperature limitation of 50°C is introduced in the isothermic warming, and slow heat increments are used, which promote participation in the heating processes of an internal heat source: the exothermic reactions of cement hydration. The length of the isothermic seasoning period depends on the type of cement and the composition of the concrete and may be determined by predicting the concrete's strength under non-stationary temperature conditions, a method developed by the Teploproyekt Institute. The initial data are experimental curves of the increments in the strength of the concrete of the design composition at various isothermic temperatures.

The engineering problems involved in implementing the methods of heating concrete in tall structures have been described in special literature [22, 91]. We will examine below particular cases of concrete seasoning in special facilities requiring new technical solutions.

A Combined Method of Electric Action (CMEA)

The development of a new method of thermally affecting concrete when erecting the ferro-concrete shafts of industrial pipes in winter is due to the structures of smoke and ventilation pipes designed by the Teploproyekt Institute for powerful state regional electric power plants and large metallurgical and chemical combines.

The special characteristic of pipes measuring 180, 250, and 320 meters in height is the two-row reinforcement of the shaft, where the thickness of the protective layer of concrete between the reinforcement and the mold is practically uniform in the area of both the external and internal surface of the pipe shaft and measures 30-50 mm.

When the objects have no steam feed sources, which preclude the use of mobile enclosures, it is also impossible to execute a system of electric heating using the shields of the inner mold (phase) and the panels of the outer mold (ground) as electrodes since the passage of an electric current between the inner mold and the inner row of the grounded reinforcement would cause overheating and dessication of the inner protective layer. The basic body of the wall between the two identical grounded electrodes (outer mold-reinforcement) will not be needed in this case.

The use of a bilateral heating mold in this case is also impossible since thermal inserts cannot be installed in the structure of the internal adjustable molds. Unilateral heating by thermal inserts of an external mold cannot be recommended when the walls of the stack shaft are from 0.2 to 0.8 m thick because of the considerable temperature gradients which occur in the heated structure.

The thermophysical study laboratory of the AUSRDI [All-Union Scientific Research and Design Institute] Teploproyekt has developed a means of ensuring a combined electric effect to accelerate concrete hardening when erecting tall ferro-concrete type shafts [29]. The essence of the method consists of using bilateral heating of the structure. In this process, the heat source to heat up the concrete of the wall from the inside is a protected layer of concrete.

The diagram of this method of combined electrical action during the heating of concrete in the shaft structure of an industrial smoke stack is presented in Figure VI.2. The shields of the internal mold which is an annular electrode are fed single-phase low-voltage current from a step-down transformer. The second low-voltage phase of the transformer is grounded. A reinforced chassis is the second grounded electrode during the electrical heating of the internal protected layer of the concrete. The external mold which is installed on two concreting strips is supplied with a two-stage heating element, supplied with electricity by a three-phase current circuit.

The concreting is carried out by strips or sections (2 strips), with simultaneous insertion of the heating elements into the external mold and transmission of current to the internal mold shields. Uniformity of the temperature field in the heated structure, which decisively affects the quality of the concrete and the service life of the facility, is ensured by

properly selecting the current voltage during electric heating of the protective layer and by properly selecting the power of the heating mold's heating elements.

During bench tests a fragment measuring 500 x 500 x 400 mm was concreted, which was designed to simulate the wall of a shaft 400 mm in thickness with double-row reinforcement and with protective concrete layer 40 mm thick.

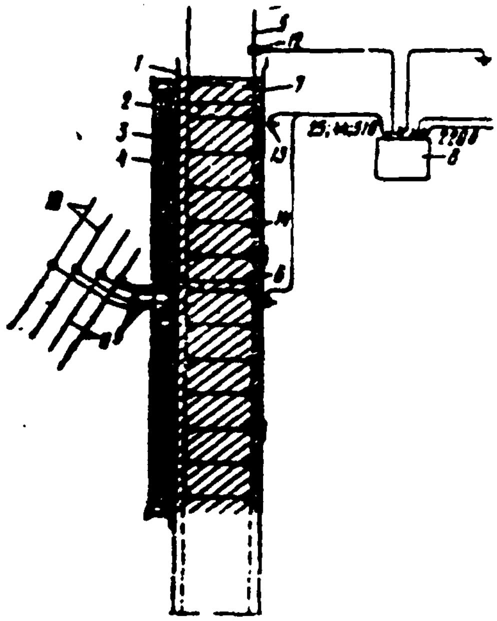

Figure VI.2. Diagram of Producing a Combined Electrical Effect While Heating the Concrete of a Stack Shaft. 1, External mold; 2, heating element; 3, mineral heat insulation; 4, veneer enclosure of the thermal insulation; 5, reinforced chassis; 6, twist joint with textolite insert; 7, internal mold; 8, TV-20 single-phase step-down transformer; 9, conduit to hook up heating elements; 10, distributor conduits of the lower stage of the panel heating mold; 11, the same, upper stage; 12, clamp to connect the conduits to the reinforcement; 13, clips on the internal mold shield; 14, internal protective thermoreactive concrete layer.

A fairly uniform temperature field was obtained during the longest bench test: isothermic seasoning of the concrete while two different heating sources acted on it. The maximum temperature variation in the concrete through the thickness of the heated wall was 10-12°C.

The intensity of the electrical field was also extremely stable throughout the protective layer, with a certain increase in the voltage drop in zones located near the reinforcing chassis rods.

These bench tests made it possible to establish the following dependency to calculate the electrical resistance of the protective concrete layer as it was electrically heated between the annular electrode of the mold and the reinforcement chassis

$$R_{pl} = \rho \frac{b}{4LH}\left(\alpha \ln \frac{h}{\pi d_0} + \frac{\pi b}{h}\right), \qquad \text{(VI.1)}$$

where ρ - specific resistance of concrete;
b - thickness of protective layer;
L - length of internal field of the stack;
H - height of concreting stage;
h - step of reinforcement installation;
d_0 - diameter of reinforcement;
α - coefficient equal to 2 with single-phase current.

The initial intensity of the electrical heating making it possible to initially season the concrete while it is being laid within the volume of one stage at a temperature of 15-20° should be equal to U = 25-30 V.

The value of the established power of the thermal insert heating coils in the panels of the external mold should be determined by nomograms [22].

This method was productively introduced in facilities of the Spetszhelezobetonstroy Trust during the erection of a stack 180 m high, the Pavlodar Heat and Electrical Power Plant No. 3 and a stack 150 m high of the Heat and Electrical Power Plant in the city Belaya Tserkov'.[1]

The electrical heating system was connected an hour before concreting of the section began; electrical warming of the protective layer was carried out as soon as concrete was put into the mold. In order to obtain a strength of 70% R_{28} before freezing of the concreted structures took place, the combined electrical action modes shown in Table VI-1 was used.

When a shaft with a wall thickness of 0.6 m was warmed using the combined electrical action method, the temperature change in the basic mass of concrete during the period of temperature increase did not exceed 14-16°C, and during the period of isothermic seasoning did not exceed 10-12°C. When concrete in a wall measuring 0.3 m thick was warmed, these changes were 5-7°C and 2-3°C, respectively.

The electrothermal activity of the warmed protective layer persists for a period which is sufficient to carry out a full cycle of thermal action on the concrete.

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[1]The work was carried out by PhD Candidate G. V. Mishin and Engineer D. Ye. Ayzenshteyn.

TABLE VI-1. MODES OF COMBINED ELECTRICAL ACTION.

Stages of Mode	Temperature in °C	Time in Hours	Voltage in V Heating	Warming
Seasoning during concreting period	20-25	8-12	49	25
Temperature in degrees	25-50	5	70	44
Isothermic seasoning	50	30-35	60	44-51
Cooling	50-10	4-10	--	25

The actual specific expenditure of electrical energy for thermally treating one cubic of concrete while it reached 70% R_{28} averaged 83.6 kwt·hr, which shows the effectiveness of using the combined electrical action method for winter concreting of ferro-concrete tube shafts with a double reinforcement mesh.

To successfully apply this method under production conditions, the following are necessary:

Proper selection of the initial voltage of the current sent to the protective cement layer, which in turn requires a special determination of the specific electrical resistance of the actual concrete composition during the initial hardening periods (the reference value of .. is 850 ohm·cm);

maintaining of the stability of the protective layer's electrical resistance both around the perimeter and throughout the height of the installation. This is achieved by more carefully monitoring the B/C value in the individual batches of concrete and by strictly determining the thickness of the protective layer (for instance, using special clamps leading from the hardening concrete, set up between the reinforcement and the mold at several points around the perimeter of the installation);

ensuring that the charge of the individual electrical supply system phases has the distribution which would reduce the phase misaligment phenomenon caused by the use of a single phase to electrically heat the protective layer. The maximum current value during electrical heating of the protective layer at a voltage of 25 V may be 3,000-3,200 a;

the absolutely simultaneous start-up, while connecting to the internal mold shields, of several single-phase transformers using a single contact or a system of synchronously operating contacts.

With allowance for these conditions, the combined electrical action method recommended both as a basic method and a reserve method for warming concrete in the shafts of ferro-concrete stacks with two-stage reinforcement makes it possible to ensure the economical, bilateral uniform heating of structures and the protective electrically heated layer of concrete and the heating mold should be used as heating sources.

Concrete Seasoning Modes in Underwater Installations

An extremely unique range of problems arises in selecting concrete seasoning methods in small and medium-sized hydrotechnical facilities located in a low-temperature water-medium. In this case no parallel can be drawn with the modes of winter concreting, but simultaneously the concrete hardening conditions in such structures also differ greatly from those of "normal hardening". This intermediate position of the concrete seasoning modes gives rise to the necessity for a specific approach to each type of structure with allowance for its size, initial and boundary conditions when the structures interact with their medium, requirements levied on speeds of interaction and concrete strength when the structure is stressed. One example is the structures of the drilled-insert piles used for deep foundation support in constructing heavy ocean berths. Each of the supports is installed on piles which are a metal cylindrical envelope measuring 1.6 m in diameter and with a wall thickness of δ = 16 mm, within which a reinforced chassis is mounted and which is filled with cast in-situ concrete underwater.

Deep anchoring of the piles is ensured by charging the envelopes from a floating conductor up to the top of the rock, by a cement tamping device in the zone where the envelope touches the rock, by boring cylindrical cavities in the rock base to lay the reinforcement and by filling the pile envelope and cavity in the rock with concrete underwater via a vertically moving tube (the VMT method).

The specific feature of constructing one of the berths which gives rise to the necessity for carrying out thermophysical investigations of the concrete hardening modes in the envelopes was the low-temperature conditions of the ocean environment which are characteristic of a polar climate. The temperature of the ocean water throughout the year varied from -2 to +8°C. Thus, the temperature conditions of the concrete hardening within the envelope were pre-determined to a great extent by the intensity of thermal exchange between the pile envelopes and the water medium. An initial determination was made of the heat exchange coefficients for two water medium motion conditions in the area where the pile envelopes were located:

a) induced motion, characteristic of the ebb and flow periods;

b) natural motion caused by the rising gravitational movement of the water medium along the envelope.

The calculations used criterion equations which characterized the conditions of heat exchange on the basis of the theory of similitude for each of the above-mentioned conditions.

For induced movement, the coefficient of thermal exchange was determined from the equation

$$\mathrm{Nu} = c\,\mathrm{Re}^{n}\,\mathrm{Pr}^{0.3}. \qquad \text{(VI.2)}$$

The boundary conditions of heat exchange during natural movement of the water medium were characterized by the equation

$$\alpha = 0{,}135\,(\beta g \,\mathrm{Pr})^{1/3}\,\frac{\lambda}{\nu^{1/3}}\,\Delta t^{1/3} \qquad \text{(VI.3)}$$

when Gr Pr > $2 \cdot 10^7$.

An analysis of the values of the heat exchange coefficients indicates the extremely high intensity of heat removal on the pile envelope and the possibility of utilizing the temperature difference characteristic of natural conditions (10-20°C) as a calculation value α = 400 kcal/m^2·hr·°C for both conditions of motion of the water medium.

Under these conditions laying heated concrete mixtures into a metallic envelope leads to intense cooling of the concrete in the peripheral zones, especially in a protective concrete layer with a thickness of δ = 0.12 m.

The heat losses during the initial periods after concreting of a pile 20 m high are approximately 600,000 kcal/hr. This intense heat removal is unavoidably reflected as well as in the temperature of the concrete at the center of the massive pile structure (M = 2.5 m^{-1}), preventing the development of exothermic reactions of cement hydration in the concrete.

The nature of temperature distribution in the concrete of piles with a metallic envelope when the pile structure made contact with the low-temperature medium was determined when thermophysical industrial studies were carried out on one of the facilities (Figure VI.3).[2] Temperature measurements were taken by remote temperature sensors: chromel-copel thermocouples connected to an EPP-09 electronic recording potentiometer. Thermocouples were installed in the ferro-concrete structure of the pile during the underwater concreting operation with the aid of special attachments. Thermocouples were attached to the external surface of the envelope and inserted into the water medium by divers.

The piles were concreted using hydroengineering concrete, brand 300. The necessary plasticity of the concrete mixture, 22 cm OK [Translator's Note: expansion unknown] at B/C = 0.4 was obtained by increasing the expenditure of cement -- 600 kg/m^3 and by adding 0.18% sulfite-liquor waste.

Initial temperature of the laid concrete mixture due to heat losses during transport and laying via a concrete-laying tube was 10°C. At a water temperature of 4°C, the temperature of the concrete at cross-section I-I (Figure VI.4) in the center of the protective layer was 6°C during the first period. The time when internal heat emission began in the concrete was noted 10 hours after the end of concreting, and reached its maximum two days later. However, the

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[2] The work was carried out by PhD Candidate I. V. Dudinkov.

temperature in the concrete mass did not exceed 20°. The development of exothermic reactions in the mass caused some increases in the concrete temperature in the protective layer (by 2-3°C), which began to drop again two days later.

The concrete strength calculation carried out by PhD Candidate (Technical Science) B. D. Trinker and Engineer V. A. Shvyryayev, showed that the rise of concrete to a strength of 50% R_{28}, which is necessary for the pile to tolerate mechanical loads (vibration, shock, waves, ice) proceeds fairly slowly. Thus, concrete in the protective layer acquires the necessary strength in 10-15 days, which does not protect the structure of the pile from disruption of the casting and strength of the concrete bond to the reinforcement and the envelope when operations on installing and concreting the pile on the pontoon conductor are carried out jointly. Thus, there arises the necessity for accelerating hardening of the concrete in the pile under conditions where it is in contact with the low-temperature water medium. This conclusion does not extend to the pile elements in contact with the rock base.

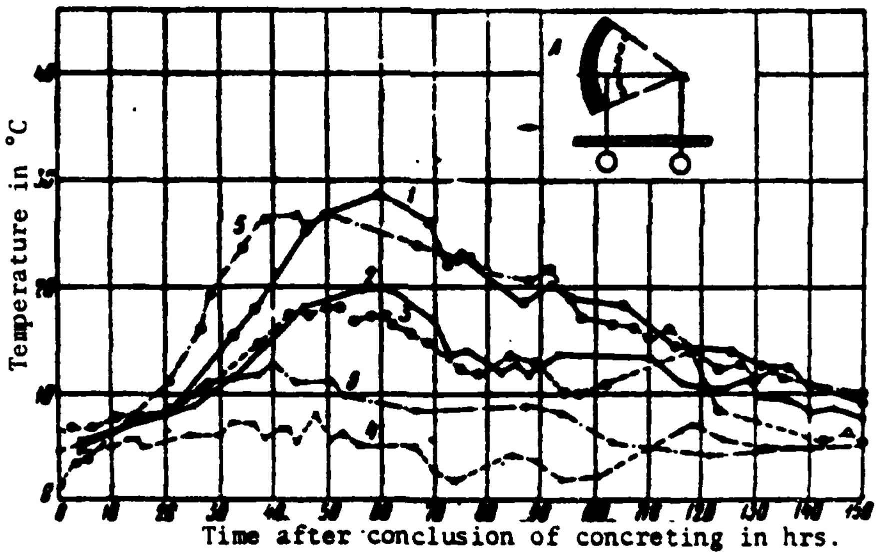

Figure VI.3. Temperature Distribution in the Underwater Structure of a Pile with Various Methods of Seasoning. 1, 2, With Peripheral Electrical Heating; 3, 4, Natural heating; 5, 6, With Thermal Insulation. Solid lines -- temperature in the peripheral layer; dotted lines -- temperature in the center of the pile. A, Diagram of the location of the thermocouples.

The temperature measurements carried out in cross-section II (see Figure VI.4) showed that the total level of the temperature field in this zone was considerably higher than in the zone where there was contact with the water medium. The lower loss of heat where the concrete is in contact with the rock base promotes the development of exothermic reactions, which causes the temperature in the concrete mass to increase to 35-40°C and in the protective concrete layer to 30-35°C.

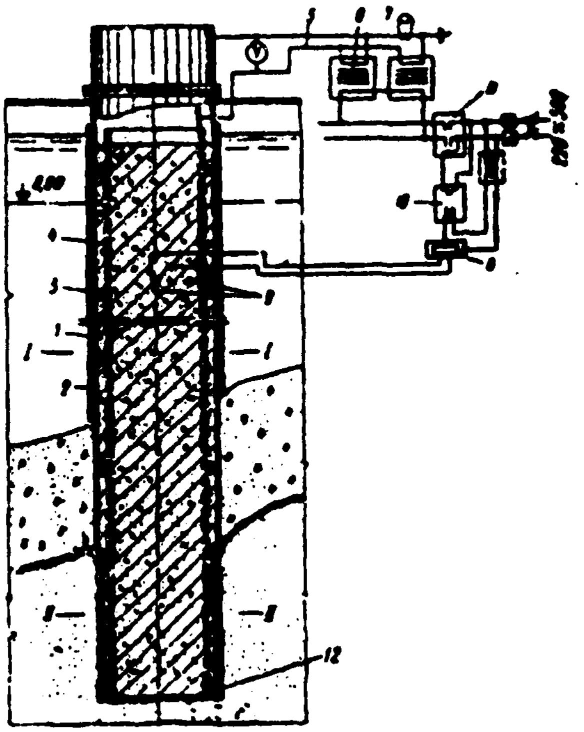

Figure VI.4. Diagram of Peripheral Electrical Heating of Concrete in a Pile Structure. 1, Metal envelope; 2, reinforcement; 3, textolite guides; 4, thermal insulation; 5, low-voltage cables; 6, step-down single-phase transformer; 7, grounding cable; 8, contact galvanometer; 9, differential thermocouples; 10, intermediate relay; 11, contact; 12, insulating supports.

Thus, the difference in boundary heat exchange conditions throughout the height of the pile leads to the appearance of a temperature difference in the concrete which is up to 30-35°C and leads to the appearance of temperature stresses in concrete of various ages.

In order to eliminate great temperature changes throughout the height of the pile, thermal insulation of its metal envelope wherever it is in contact with the water medium was suggested. In principle, two types of imsulating materials can be used to provide thermal insulation of underwater objects (wetting and non-wetting materials). The most advisable type of wetting insulation is a mineral felt which in its dry state at a volume weight of γ_M = 150 kg/m^3 has a coefficient of heat transfer of λ_M = 0.05 kcal/m·hr·°C.

When the thermal insulation operates underwater, its coefficient of thermal conductivity will be [90]

$$\lambda_{w} = \frac{1}{\frac{1-\psi}{\lambda_{s}} + \frac{\psi}{\lambda_{b}}}, \qquad \text{(VI.4)}$$

where ψ - optimum material porosity in %;

λ_s - thermal conductivity coefficient inherent in a mineral fiber in kcal/m·hr·°C

λ_w - thermal conductivity coefficient of water in kcal/m·hr·°C.

Consequently, for mineral felt

$$\lambda = \frac{1}{\frac{0.1}{4} + \frac{0.9}{0.5}} = 0.548 \text{ kcal/m·hr·°C}.$$

It is advisable to use a porous rubber as a non-wetting insulation: γ_r = 400 kg/m^3; λ_r = 0.07 kcal/m·hr·°C.

During the productivity investigations two types of insulations were tested. By calculating the effective coefficient of heat tranfer based on the necessity for reducing the intensity of thermal exchange by approximately 100 times when the envelope made contact with the water, the optimum insulation thickness was determined. The effective coefficient of thermal transfer was calculated [3] according to the formula

$$\alpha_{ef} = \frac{\lambda_i \alpha_i}{\lambda_i + \delta_i \alpha_i}, \qquad \text{(VI.5)}$$

where λ_i is the thermal conductivity coefficient of the insulation underwater in kcal/m·hr·°C;

δ_i is the thickness of the insulation in m;

α_i is the thermal exchange coefficient on the free insulation surface in kcal/m^2·hr·°C.

In practice the reduction in the heat transfer coefficient from α_i equals 500 kcal/m^2·hr·°C to $\alpha_{ef} \approx 4$ kcal/m^2·hr·°C was ensured by the use of insulation made of mineral felt with a thickness of δ_i = 0.1 m or made of porous rubber with δ_i = 0.02 m.

As productivity tests showed (see Figure VI.3), at an initial concrete mixture temperature of +6°C the temperature in the mass reached 35°C after 40 hours, and the temperature in the protected layer reached 15°C.

Thus, the use of thermal insulation for the underwater portion of the pile intensifies hardening of the concrete in the envelope and creates identical thermal conditions in the concrete throughout the height of the pile. However, even in this case the concrete in the protective layer acquires the required strength only 7 days after concreting is completed [71].

An effective method of accelerating hardening of cast in-situ ferro-concrete piles in metal envelopes was electrical warming of the protective layer of concrete in conjunction with thermal insulation [30, 99].

Electrical warming of the insulating layer was carried out using the reinforcement (phase) in the metal envelope (ground) as electrodes (see Figure VI.4). Contact between them was prevented by replacing the metal support-clamps of the reinforcement by textolite ones. The number of transformers and the system by which they were interconnected were determined by calculation as a function of the change in the value of the specific electrical resistance of the hardening concrete and the speed at which warming took place.

Electrical warming was begun 18-20 hours after concreting of the pile was finished, as a result of which maximum effect was achieved in reducing the temperature gradient throughout the cross-section of the pile and in reducing the expenditure of electrical energy. In this case the section of the pile in contact with the rock and having favorable temperature conditions of natural seasoning is not subjected to electrical warming (there is no metal envelope).

The protective layer was warmed at a speed of 3-5°/hr to a temperature near the temperature of the concrete in the central portions of the pile; this temperature was reached due to exothermal reactions in the concrete before the electrical warming was begun. Then warming was carried out in such a way that the concrete temperature in the protective layer was 5-8°C below the temperature of the basic mass.

The total period of electrical warming was 20-25 hours. The concrete in the protective layer acquires the necessary strength under electrical warming within 3 days after concreting is concluded.

The data of these tests are evidence of the fact that electrical warming of the protective layer influences the temperature in the central zones of the mass with a certain lag. Under conditions where the protective layer is moderately warm, it is not so much a source of warming for the basic mass, but rather performs the role of inactive heat-insulating layer and aids in the more active development of internal thermal emission in the concrete under near-adiabatic conditions. In connection with this a limitation is also introduced on the warming temperature of the protective layer (30-35°C), which prevents the process of internal heat emission from developing with intolerable intensity and prevents the temperature in the mass of concrete from exceeding 40-45°C.

Thermal emission in the basic mass is calculated on the basis of the data of experimental studies which were obtained under non-stationary temperature conditions (an example of such a study for conditions where a structure was seasoned underwater is given in Chapter IV).

Thus, a new approach is revealed to seasoning medium-sized underwater concrete structures in a low-temperature medium, with which artificial warming of the protective layer performs the role of regulating the intensity with which the natural hydration processes develop in the basic mass of the installation.

The possibility of controlling the hardening modes of the concrete during the actual use of seasoning using the "Thermos" method for the basic mass of concrete opens new perspectives for selecting optimum temperature conditions in each specific case. Optimization of the condition should be based on a combination of favorable heat-pressure conditions in the structures [20] and ensuring that the concrete acquires the necessary strength within the established time periods.

Winter Concreting of the Moscow Television Tower

The erection of a unique television tower 533 m high for the Moscow television station engendered a number of new engineering problems, including ones in the area of the winter concreting of the complex cast in-situ ferro-concrete structure of the tower.

The ferro-concrete structure of the tower consists of a conic base (mark 0-63 m) and a high shaft (mark 63-385 m). The lower portion of the conic base is designed in the form of 10 support structures (legs) measuring 17.3 m in height. At the 42 m mark the conic base has a diaphragm ring which absorbs force from the anchoring of the pre-stressed reinforcing cables; at the 63 m mark there is also a ferro-concrete diaphragm measuring 18 m in diameter and 1 m in thickness. Along the axis of the conic base and throughout the height of the tower there is a full ferro-concrete shaft measuring 7.5 m in diameter.

The fact that the structural elements of the tower differed so radically from each other and the special features of erecting them gave rise to the necessity of using a single universal method of winter concrete seasoning.

In the thermophysical study laboratory of the AUSRDI Teploproykt, methods were developed and suggested for thermally influencing the concrete for each of the basic elements of the facility, since concreting of the tower was carried out throughout the year, including during the 3 winter periods [100].

The methods developed (Figure VI.5) and the recommended modes of thermally affecting the concrete made it possible to ensure the required construction speeds and to maintain the high concrete engineering properties required for the structures to last a long time. With the design brand of concrete 400, under winter conditions acquisition of 70% R_{28} was ensured, while the frost-resistance index MRZ remained at 500 (the composition of the concrete and the study of its engineering properties were carried out by PhD Candidate (Technical Science) B. D. Trinker).

Of the six elements in the cast in-situ portion of the tower, five were erected using thermal effects on the concrete, and the support structures ("legs") which were erected exclusively during the summer comprised the exception.

Some of the recommended methods of thermal interaction had already been used previously to erect tall cast in-situ facilities and ensured the necessary degree of reliability in concrete seasoning. Thus, while the first element of

the facility's central shell, the cylindrical shaft (mark 0-63) was being erected, a concreting method using a mobile structure (see Figure VI.5, position V) was used, which had worked out well in constructing cast in-situ ferro--concrete stacks under winter conditions. During concreting of two large elements, the diaphragm rings (marks 42 and 63 m) of the tower, large-capacity stationary structures were used.

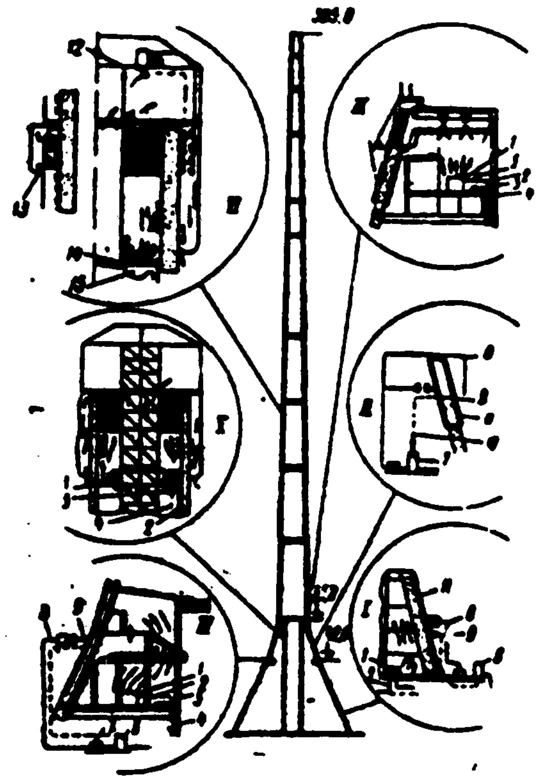

Figure VI.5. Methods of Thermally Affecting Concrete While Erecting a Television Tower Under Winter Conditions. I, Unilateral electrical heating and temporary structure for erecting the support-"legs"; II, bilateral electrical heating of the envelope of the conic base in a three-stage mold; III, large-capacity enclosure during concreting of the diaphragm; IV, large-capacity enclosure and unilateral electrical heating during concreting of the diaphragm ring; V, mobile enclosure while erecting shells; VI, combined heating of the concrete of the tall shaft. 1, Heating assembly; 2, steam supply; 3, condensate tap; 4, condensate supply; 5, nozzle through which steam is fed to humidify the air; 6, automatically operating shield; 7, TMO-50 tranformer; 8, low-voltage wire; 9, heat signal system; 10, signal line; 11, mold shield with thermal insert; 12, high-voltage cables; 13, intermediate tank; 14, flexible steam line sleeve; 15, flexible condensate line sleeve.

When the other elements of the television tower were erected, new methods of thermally influencing concrete were used for the first time:

bilateral electrical heating in pre-stage mold with simultaneous heating of the concrete inside two strips;

combined heating of concrete.

Electrical heating in a three-stage mold (see Figure VI, position II) was developed for the conditions where the envelope (mark 16.3-63 m) of the tower's conic base was erected.

As previously noted, when using single-stage heating, a reduction in temperature, which is especially significant when the wall is more than 300 mm thick, is noted in the zone of the working seams. Data from natural observations were supplemented by solution of the problems using analog computers [31]. A temperature field is shown in a model during bilateral heating of a zone 1 m high and with a wall thickness of 500 mm (Figure VI.6, a).

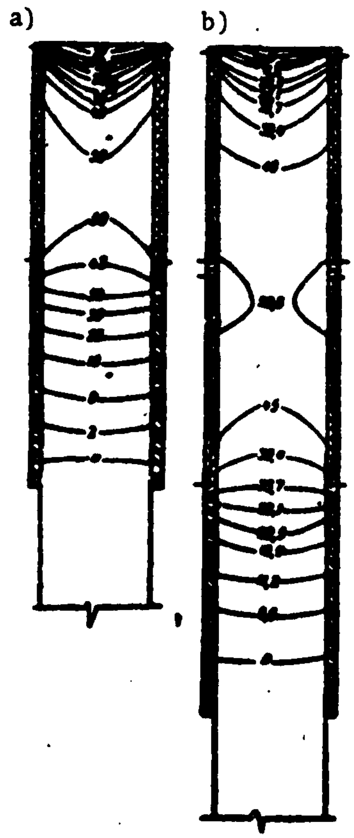

Figure VI.6. Temperature Fields in the Wall of the Envelope When the Concrete is Simultaneously Heated. a, In one zone; b, in two zones.

When the external air was at a calculated temperature of $t_e = -20°C$, the temperature difference between the central zone and the upper end of the strip

was 40-50°C. In addition to the temperature stresses and possible deformations which can occur in this case, a low temperature value in the area of the concreting seam causes the strength of the concrete to be uneven before freezing.

In addition, when the facilities are erected with single-stage heating of the concrete, unavoidable long-term interruptions are noted in the heating, which are caused by preparing the next stage of the facility for concreting (8-16 hours). During this time the concrete in the previously warm zone cools off, and the danger arises that it may freeze, which makes it impossible to lay the concrete of the next stage of the facility.

All of these drawbacks are eliminated if we use two-stage heating, during which the concrete is simultaneously heated in two zones of the facility. In the upper and middle stages of the mold, the concrete is warmed at a temperature of 45°C, and the lower stage of the mold plays the role of heat insulation, which helps the concrete cool more slowly after warming.

The nature of the temperature field in the zone of the working concreting seam in the case of two-stage heating changes sharply (Figure VI.6, b). Uniformity of a field throughout the area of the two zones is practically ensured, which is especially important for the formation of a solid concreting seam. Two-stage heating makes it possible, in addition, to considerably increase the speed with which the facility is constructed under winter conditions. Thus, in constructing the envelope of the conic base, the following conditions of thermal interaction obtained: 4 hours of seasoning the freshly laid concrete in the mold at 20-25°C, 5-6 hours to increase the temperature to 45°C, 13 hours of isothermal warming and cooling for 2 hours. The use of two-stage heating made it possible to ensure a concreting speed of 1.5-2 m/day for the envelope.

Under the actual conditions under which the tower was constructed, this heating method was used in concreting the envelope of the conic section during the 1964-1965 winter, from mark 35 m to mark 63 m.

The total number of thermal inserts in the three stages of the bilateral heating mold was 1240. The optimum electrical power of the heating element of the thermal insert, established by calculation, was 0.8 kWt. In order to increase the safety of the operations and to make it more possible to change the power of the heating elements, they were supplied with electricity by TMO-50 step-down transformers with two secondary-voltage stages: 91.5 and 62 V. In order to increase temperature uniformity during electric heating of the concrete, the mold was divided into individual sections around the perimeter of the envelope, with each section being operated by an automonous system of electrical supply linked by common control equipment.

Each electrical supply system consisted of a step-down transformer (TMO-50), an automatic unit for temperature regulation, cable line stand pipes PRG-500-3 (1 x 95), distributor wires PRG-500-3 (1 x 35) and wires to the thermal insert heating elements (KRPT-2 x 2.5).

At the beginning of the concreting, the total number of electrical supply systems was 16 units, and as the concreting of the envelope proceeded and the diameter of the facility narrowed, it dropped to 10 units.

During the time when the tests of the two-stage electrical heating were being carried out, changes were introduced into the proposed methods of seasoning concrete. Primarily: a daily cycle of concreting the strip of the envelope proved to be technologically unfeasible. As the length of the cycle was increased to 2-3 days, it was necessary to limit one's self to heating the concrete within a single stage or to reduce the isothermal seasoning temperature.

From the viewpoint of the necessity for retaining the concrete's good engineering properties, especially in the areas of the concreting seams, it proved to be more advisable to reduce the isothermic warming temperature to 30° and to carry out two-stage heating of the concrete over a period of 64-72 hours. In order to protect the end from considerable cooling at such moderate concrete temperatures, the most effective solution proved to be to shift the concreting seam 10 cm below the upper rim of the mold. In this case heat removal during air cooling is reduced, and the open upper zones of the mold's heated shields ensure infrared irradiation of the end of the wall, thus increasing its temperature by 10-15°C.

In order to keep from exceeding the isothermal warming temperature, automatic concrete temperature regulation control systems were widely used. The strength of the concrete after heating varied within the limits of 260-330 kgs/cm^2, and after 28 days was 380-415 kgs/cm^2. As a whole, 1,086 m^3 of concrete of a total volume of 2,150 m^3 were placed into the envelope of the conic portion under winter conditions, and in doing so the speeds with which the envelope was erected in summer and in winter were practically identical.

Combined heating (see Figure VI.5, position VI) of concrete was developed to erect the tall tower shaft (mark 63-385 m). The essence of this method consists in the fact that, in addition to creating a mobile enclosure of positive environmental temperatures (15-20°C), the concrete mixture placed into the metal mold is subject to local heating by the external mold panels which are equipped with thermal inserts with electrical heating elements. When seasoning the concrete in the mobile enclosure, the temperature of the medium in the suspended covering (skirt) differs by 10-15° from the temperature within the shaft, which leads to early freezing of the concrete in the protective layer. This danger is especially great during operations at great heights (250-380 m) under conditions where there are severe wind stresses. With the combined heating method there is no such temperature difference.

The use of unilateral electrical heating along with a mobile covering ensured uniform concrete strength throughout the thickness of the wall and, if necessary, created a reserve system of heating, thereby increasing the reliability with which the concrete was seasoned in the most important element of the facility.

Supplying water vapor to an altitude of 350 m in order to provide heat for the steam heaters set up in the concreting area was a complex technical problem which demanded reliable solutions both with regard to sending the steam up and bringing the condensate down. The proposed system of heat supply was graduated in design, which made it possible to solve the problems of compensating for thermal expansion of the pipelines and to guarantee drainage of the by-product condensate when the condensate drains were set up at the impasse point of each stage.

In contrast to the previously used collapsible-shield mold, in erecting the high shaft a large-panel mold was used which made it possible to constantly concrete a section of the shaft 5 m in height. In order to successively heat the concrete as concreting of a section proceeded, the mold was supplied with four thermal insert stages.

In order to ensure uniform heating of the concrete throughout the external perimeter of the shaft, in designing the mold panels and joining them up, a differential analyser was used to determine the maximum tolerable distance between the heating elements -- 300 mm. Heating elements with a power of 1.75 kWt/m^2 within the limits of each stage were united by an independent electrical supply system. The established power of the transformers and the number of automatic systems made it possible to simultaneously heat the structure within the limits of two stages.

When the shaft was being erected in winter, the connection of the electrical mold was reserved for the case when there was a temperature drop in the suspended covering, associated, for instance, with shut-down of the heaters or with large wind stresses when the temperature of the external air was low. Therefore the investigations of the temperature fields in concrete when the shaft was electrically heated were carried out at relatively low environmental temperatures in the enclosure (2-8°C). In order to maintain the calculated temperature difference between the concrete and the external environment (45-20° = 25°C), warming of the shaft structure was limited to a temperature of 30°.

During continuous concreting of four stages of a five-meter section which continued for 30-36 hours, under the most unfavorable conditions concrete is found in the fourth stage which has a well-developed cooling surface. In addition, the speed with which strength increases in this stage predetermines the time at which the mold is next raised. The use of electrical heating considerably improves the hardening conditions of the concrete in this stage, while the temperature difference throughout the thickness of a 400 mm wall does not exceed 10-15°C.

The mold was next raised 26-30 hours after concreting of the fourth stage of the section was completed.

As a whole, the method of combined heating considerably increased the reliability of the concrete seasoning modes during the winter concreting of a high shaft and ensured a construction speed for the facility which was the same as in summertime. This method is presently being used to erect industrial towers of 320 m in height.

In all, when erecting the cast in-situ elements of the television tower, 3400 m^3 of concrete of a total volume of 9500 m^3 were laid in winter. These methods and conditions of thermal interaction made it possible to maintain good engineering properties for the concrete.

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